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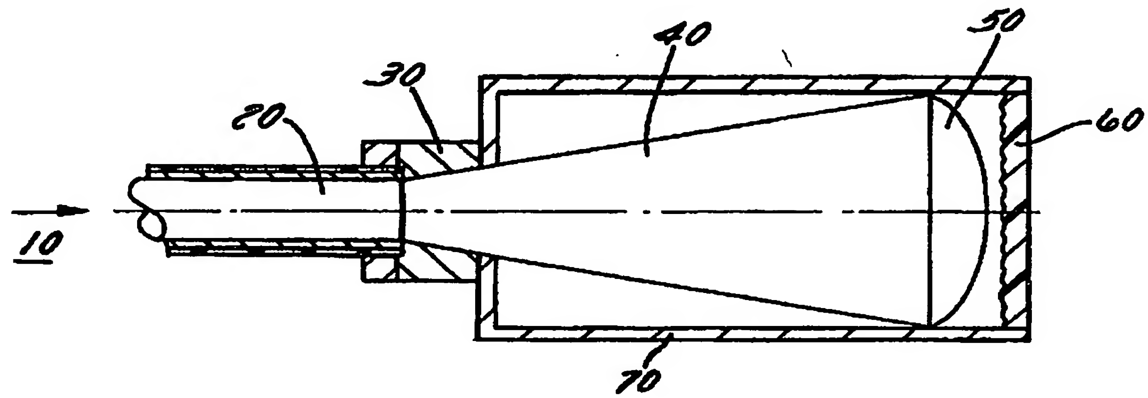

(57) Abstract

A solid integrated beamformer includes a solid nonimaging optic (40) having (i) a proximal nonimaging end and (ii) a distal nonimaging end; a solid refractive optic (50) integrally attached to the distal nonimaging end, the solid refractive optic including a distal refractive end; and a holographic surface diffuser (60) integrally formed on the distal refractive end. The solid integrated beamformer providing advantages in the precise light distribution is obtained with a compact and relatively inexpensive unitary optical device.

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INTEGRATED BEAMFORMER AND METHODS OF MANUFACTURE THEREOF

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates in general to the field of lighting. More particularly, the present invention relates to beamformers for remote source lighting. Specifically, a preferred embodiment of the present invention relates to a solid integrated beamformer having a surface diffuser. The present invention thus relates to beamformers of the type that can be termed integrated.

2. Discussion of the Related Developments

Within this application several publications are referenced by arabic numerals within parentheses. Full citations for these, and other, publications may be found at the end of the specification immediately preceding the claims. The disclosures of all these publications in their entireties are hereby expressly incorporated by reference into the present application for the purposes of indicating the background of the present invention and illustrating the state of the art.

In 1880, William Wheeler was granted a patent for a mechanism for "piping" light from a central light source to a number of locations through pipes lined with a reflective coating(1). Not until 1970, however, and after the successful production of the first truly low-loss, glass optical fibers with diameters about the thickness of a human hair, did remote illumination become practical.

Although remote source lighting (RSL) systems have recently received attention from various researchers and manufacturers, their major efforts have been focused on developing only two of the three RSL subsystems namely, the illuminator and the optical fiber. The third subsystem, the distal end device, has remained limited to conventional multi-element refractive lens implementations.

Nonimaging optics (NIO) were first developed for the detection of Cerenkov radiation in high energy physics experiments in the mid 1960s(2-4). The basic problem being addressed then was to couple light emitted over a wide area, typically 1 m^2, onto a photomultiplier with an area of a few cm^2. The principal area of development of nonimaging optics since then has been in the concentration of solar energy for heating and photovoltaic power conversion(5-6). Other

applications of nonimaging optics have included infrared communications receivers, fiber optic coupling and luminescent concentrators for integrated devices[7-9]. Nonimaging optics have also been extended to include tapered optical fibers for fiber optic sensors[10-13].

Recent progress in i) developing efficient light sources and ii) manufacturing optical fiber has permitted the assembly of an RSL system in which one, or more, optical fibers are used to deliver light to one, or more, remotely located points. The distal end of each optical fiber can be used for illumination directly or in conjunction with refractive lenses, to approximate the light distribution required by a given application. Typically, the cleaved open end of a plastic optical fiber produces a light cone with a solid angle of from 50° to 80°, depending on the core and cladding materials of the fiber. A separate refractive lens can be located near such an end. However, using a lens to shape light from the end has caused problems of light loss and overly complicated lens designs. Therefore, the previous RSL systems are limited to end uses where a highly precise illuminance distribution is not required. Heretofore, the above-discovered problems have ruled out such RSL applications as navigation lighting, obstruction lighting, signal lighting and airport approach lighting.

Applications where precise light distribution is required, (i.e., high-definition (HD) Lighting), must provide high efficiency illumination within precisely specified requirements. These requirements include: intensity distribution across the light pattern; light pattern shape; angular distribution of light in horizontal and vertical directions; and light color. Heretofore, RSL systems have not been able to meet these requirements. Therefore, what is needed is a RSL system having distal ends that provide precise light distribution, (i.e., high definition).

The below-referenced U.S. patents, and patent application, disclose embodiments that are satisfactory for the purposes for which they were intended. The disclosures of all the below-referenced prior United States patents, and patent application, in their entireties are hereby expressly incorporated by reference into the present application for purposes including, but not limited to, indicating the background of the present invention and illustrating the state of the art.

U.S. Pat. No. 4,309,093 discloses a method of replicating a diffusing plate. U.S. Pat. No. 4,336,978 discloses a method for optically making a diffusion plate. U.S. Pat. No. 4,898,450 discloses an expanded beam nonimaging fiber optic connector. U.S. Ser. No. 08/636,798 discloses a universal remote lighting system. U.S. Pat. No. 5,365,354 discloses method of making a grated refractive index type diffuser based on volume holographic material. U.S. Pat. No. 5,534,386 discloses a homogenizer formed using coherent light and a holographic diffuser.

SUMMARY AND OBJECTS OF THE INVENTION

By way of summary, the present invention is directed to a solid integrated beamformer that combines nonimaging optics, refractive optics and a surface diffuser for shaping light. The present invention is also directed to methods of manufacturing the integrated beamformer. An effect of the present invention is to reduce the size and weight of the assembly, as well as its complexity, by joining together the diffuser, refractive optics and nonimaging optics in a single unitary device.

The advantages of the present invention include fewer parts combined with a reduction in size and/or weight and a reduction in cost. These advantages will be appreciated in both military and commercial lighting applications. For example, the benefits of a shipboard navigation lighting system according to the present invention include: the elimination of the need for a separate diffuser mounting bracket, a corresponding reduction in the size and mass of the enclosure; and a corresponding reduction in topside weight and moment. In addition an RSL system according to the present invention may require less maintenance and have a longer useful life.

A primary object of the invention is to provide an apparatus that combines nonimaging optics, refractive optics and a surface diffuser into a single unitary component. Another object of the invention is to provide an apparatus that is cost effective. It is another object of the invention is to provide an apparatus that is rugged and reliable, thereby decreasing down time and operating costs. It is yet another object of the invention is to provide an apparatus that has one or more of

the characteristics discussed above but which is relatively simple to manufacture and assemble using a minimum of equipment.

In accordance with a first aspect of the invention, these objects are achieved by providing a solid integrated beamformer including: a solid nonimaging optic having i) a proximal nonimaging end and ii) a distal nonimaging end; a solid refractive optic integrally attached to said distal nonimaging end, said solid refractive optic including a distal refractive end; and a surface diffuser integrally formed on said distal refractive end. The invention also includes apparatus that incorporates the solid integrated beamformer.

Another object of the invention is to provide methods that can be used to manufacture the integrated beamformer. It is another object of the invention is to provide methods that are predictable and reproducible, thereby decreasing variance and operating costs. It is yet another object of the invention is to provide methods that have one or more of the characteristics discussed above but which are relatively simple to setup and operate using moderately skilled workers.

In accordance with a second aspect of the invention, these objects are achieved by providing a method comprising: providing an optical blank with a nonimaging optic and a refractive optic, said refractive optic having a distal refractive surface; providing a surface diffuser master; contacting said distal refractive surface with said diffuser master; and removing said diffuser master from said distal refractive surface so as to replicate said surface diffuser master. The invention also includes apparatus for carrying out the replication of the surface diffuser on the distal refractive surface, or alternatively, molding, or casting the surface diffuser so as to integrally form the surface diffuser.

These, and other, aspects and objects of the present invention will be better appreciated and understood when considered in conjunction with the following description and the accompanying drawings. It should be understood, however, that the following description, while indicating preferred embodiments of the present invention, is given by way of illustration and not of limitation. Many changes and modifications may be made within the scope of the present invention without departing from the spirit thereof, and the invention includes all such modifications.

BRIEF DESCRIPTION OF THE DRAWINGS

A clear conception of the advantages and features constituting the present invention, and of the construction and operation of typical mechanisms provided with the present invention, will become more readily apparent by referring to the exemplary, and therefore nonlimiting, embodiments illustrated in the drawings accompanying and forming a part of this specification, wherein like reference numerals designate the same elements in the several views, and in which:

FIG. 1 illustrates a schematic view of a beamformer;

FIG. 2(a) illustrates an isometric view of a solid integrated beamformer according to the present invention;

FIG. 2(b) illustrates a micrographic view of a submicron holographic diffuser surface relief embossed on a spherical surface lens of the solid integrated beamformer depicted in FIG. 2(a);

FIG. 3(a) illustrates light transformer diameter according to the present invention as a function of divergence angle for several common fiber diameters;

FIG. 3(b) illustrates light transformer length according to the present invention as a function of divergence angle for several common fiber diameters;

FIG. 4(a) illustrates relative intensity of light transmitted by optical fiber as a function of divergence angle for two common fiber numerical apertures;

FIG. 4(b) illustrates total intensity of light transmitted by optical fiber as a function of divergence angle for two common fiber numerical apertures;

FIG. 5 illustrates a schematic view of the surface contour of a compound parabolic concentrator according to the present invention;

FIG. 6 illustrates a schematic view of the reflection geometry for a compound parabolic concentrator conical section according to the present invention;

FIG. 7 illustrates a schematic polar coordinate system used to calculate a compound parabolic concentrator parabolic curve according to the present invention;

FIG. 8 illustrates a geometric construction used to derive Eq. (7) according to the present invention;

FIG. 9 illustrates a schematic of a general surface contour for a nonimaging optic/lens combination according to the present invention;

FIG. 10(a) illustrates isometric 3-D display of the performance of an elliptical non-Lambertian holographic surface diffuser according to the present invention;

FIG. 10(b) illustrates a pattern photo from the diffuser used to generate the performance data illustrated in FIG. 10(a);

FIG. 11(a) illustrates a microphotograph of a holographic surface relief from a circular non-Lambertian holographic surface diffuser according to the present invention;

FIG. 11(b) illustrates a microphotograph of a holographic surface relief of an elliptical non-Lambertian holographic surface diffuser according to the present invention;

FIG. 12 illustrates a perspective view of a non-Lambertian holographic surface diffuser recording geometry using a rectangular diffuser aperture according to the present invention;

FIG. 13 illustrates the reading geometry for a beam scattered by non-Lambertian holographic surface diffuser according to the present invention;

FIGS. 14(a)-(g) illustrates a nickel electroforming technique sequence for submicron surface relief replication of a non-Lambertian holographic surface diffuser according to the present invention; and

FIG. 15 illustrates a schematic view of an automatic light scattering apparatus for the characterization of nonimaging optics/holographic surface diffuser combinations according to the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

The present invention and the various features and advantageous details thereof are explained more fully with reference to the nonlimiting embodiments described in detail in the following description. Descriptions of well known components and processing techniques are omitted so as to not unnecessarily obscure the present invention in detail.

1. System Overview

The above-mentioned requirements are mutually contradicting and cannot be satisfied simultaneously in the case of the assembly of a separate diffuser with a separate refractive element and separate nonimaging optics. However, it is rendered possible to simultaneously satisfy these requirements to a certain extent by employing a solid integrated beamformer according to the present invention in consideration of the fact that the nonimaging optics, (NIO), refractive optics, (RO) and light shaping diffuser (LSD) are all joined together into a single unitary device.

2. Detailed Description of Preferred Embodiments

To improve beamformer performance, and significantly reduce the cost of production, the present invention includes several alternative processing approaches that will result in the fabrication of a solid integrated beamformer with a holographic microstructure replicated on its surface.

Referring to the drawings, it can be seen that the present invention is a surface diffuser formed on refractive optics. It should be noted that the features illustrated in the drawings are not necessarily drawn to scale.

Referring to FIG. 1, a nonintegrated distal end device to provide high-definition remote source lighting (HD RSL) can consist of three separate components. These three discrete optical parts include: a non-imaging light transformer to reduce the divergence angle of the light emerging from an optical fiber; a spherical convex lens to reduce the physical size of the device; and a non-Lambertian holographic diffuser to shape the light into the desired pattern. The beamformer assembly consists of three major elements: the optical connector, enclosure, and some support hardware. Depending on the holographic recording conditions, the diffuser can shape the outgoing light into circular, elliptical, linear, or even square patterns with a wide range of angular distributions (from 1° to 100°) along both axes, independently.

Still referring to FIG. 1, light 10 traveling along optical fiber 20 passes through optical connector 30. Nonimaging light transformer 40 is connected to optical fiber 20 within optical connector 30. Light travels into nonimaging light transformer 40 from optical fiber 20 across the interface between these two

components. Spherical convex lens 50 is connected to nonimaging light transformer 40. A non-Lambertian holographic diffuser 60 is located downstream of spherical convex lens 50. The non-Lambertian holographic diffuser 60, the spherical convex lens 50 and most of nonimaging light transformer 40 are assembled within enclosure 70.

However, a number of shortcoming are inherent to this nonintegrated, separate component design. First, the losses due to Fresnel reflection may be as high as 16% because of the number of surfaces. Second, producing the light transformer by machining limits the shape of the light transformer device to relatively simple surface shapes, thereby causing higher light loss than is necessary. Third, the overall cost of the resulting beamformer is driven up by the expensive, necessarily labor intensive, assembly of the separate components. What is needed, therefore, is the combination of fiber optic/NIO/lens/diffuser through the full integration of the NIO/lens/diffuser components. The present invention is directed to this approach, thereby permitting the optimization of the efficiency of the optical system together with streamlined design and more cost effective production of the beamformer. These advantages will lead to the popularization of HD RSL systems.

In comparison to the separate component approach, the solid integrated beamformer has up to a 20% improvement in efficiency and vastly reduced manufacturing costs. The approach represented by the present invention is to integrate three previously separate and discrete beamformer components (the light transformer, the lens, and the diffuser) into one solid integrated beamformer (SIB) optical element. In order to achieve this result, several techniques for submicron surface relief replication on a curved surface are discussed below.

Referring to FIG. 2(a), a solid integrated beamformer 80 is depicted. The solid integrated beamformer (SIB) includes a sophisticated combination of parabolic and hyperbolic surfaces for a non-imaging light transformer integrated with a convex lens 90 in a molded body 100. Referring to FIG. 2(b), a submicron holographic diffuser surface relief (shown at magnification x1000) is embossed on the spherical surface of the lens. However, the surface of the lens can be

aspherical, provided that the shapes of the other surfaces are correspondingly modified.

As a result of the above-described integration, the production of a key element of High Definition Remote Source Lighting (HD RSL) systems (i.e., the distal end), will be streamlined. The resulting distal end optical device, (i.e., a solid integrated beamformer with much higher efficiency), will be able to be mass-produced at a very low cost. Such a beamformer will make it possible to implement remote source lighting for high-definition lighting. Remote source lighting has a number of benefits: ease and low cost of handling, maintenance, and repair of conveniently located light sources; reduced electrical power consumption; major reduction in life-cycle costs; high reliability and redundancy; reduced EMI/EMP vulnerability; and heat removal from the lighting point. The present invention provides the unexpected results of both an improvement in performance and a significant reduction in the cost of production of the beamformer.

Transmission characteristics for each of the solid integrated beamformer components, as well as integrated components, can be calculated and/or measured one at a time without undue experimentation using apparatus that is disclosed below. Light losses also can be calculated and/or measured, including losses caused by differences in index of refraction between materials, one at a time without undue experimentation.

Starting from a theoretical approach, simplifications of the light transformer's surface contour and limitations can be performed, leading to an engineering solution based on low-cost and performance. Various combinations of techniques, (e.g., casting, thermoforming, injection molding, embossing) can be used to fabricate the solid integrated beamformer. Beamformer shape and surface accuracy requirements, as well as material limitations, can be optimized without undue experimentation.

a. Non-Imaging Light Transformer

The operating principle of a light transformer (LT) is based on optical "etendu" -- the product of the area and the square of the sine of the divergence angle is a constant (known as the Liouville invariant) in a closed non-absorbing optical system[1,2] represented by the following equation:

$$A \sin^2 \theta_1 = a \sin^2 \theta_2, \quad (1)$$

where A and a are the areas of the optical beam, and θ_1 and θ_2 are the divergence angles of the beam at any two points along its propagation path. In practical applications, one must also consider the length of the LT required to achieve a particular change in divergence angle. Generally, it is advantageous to minimize the length because of packaging concerns such as size and weight. The length of an LT that preserves the Liouville invariant is given by the geometric relation:

$$L = 0.5(D + d) \cot(\theta) \quad (2)$$

where D and d are the LT diameters at both ends and θ is the acceptance angle of the of the light transformer at its large diameter end. The required diameter and length as a function of divergence angle for several common fiber optic diameters are shown in FIGS. 3(a) and 3(b), where the fiber numerical aperture (NA) is 0.22.

Another important consideration is the angular distribution of the light transmitted by an optical fiber. This distribution is not uniform, but follows a Gaussian distribution, with most of the light intensity falling near the optical axis. This distribution is illustrated in FIGS. 4(a) and 4(b) for numerical apertures (NAs) of 0.22 (13°) and 0.035 (2°). The NA is defined as the angle which contains 95% of the light intensity. An NA of 0.22 is typical of a multimode fused silica fiber. This NA of 0.22 is assumed in much of the discussion that follows, but the same arguments may be extended to borosilicate and plastic fibers that have NAs near 0.5, (corresponding to a half angle of 30°). From FIGS. 4(a) and 4(b) it will be appreciated that, even for an NA of 0.035 (2°), over 60 % of the light is concentrated within the first 0.5°.

b. General Sizing Considerations

In order to develop a practical design for an LT/fiber optic coupling system, it is necessary to consider the size of the LT exit aperture, the length of the LT, and the spot size projected on the illuminated area. The spot size, S, is given by

$$S = 2\,(l) \tan\theta_2 + D, \quad (3)$$

where l is the distance to the illumination area. The apertures and lengths of NIOs for 100, 200, 400, 600, and 1000 μm core diameters for divergence angles of

0.5°, 1°, 2° and 5° calculated from Eqs. (1) and (2) are given in Tables 1(a) and 1(b). It is important to note that the length of the LT increases dramatically for narrower divergence angles. The aperture diameter and the length scale linearly with the fiber core diameter.

Table 1(a)
Light Transformer Aperture Diameters (mm) for Selected Divergence Angles and Core Sizes, Assuming a Fiber NA of 0.22

	Divergence Angle (°)			
Core Diameter (μm)	.5	1	2	5
100	2.52	1.26	0.63	0.25
200	5.04	2.52	1.26	0.504
400	10.08	5.04	2.52	1.01
600	15.13	7.56	3.78	1.51

Table 1(b)
Light Transformer Lengths (mm) for Selected Divergence Angles and Core Sizes, Assuming a Fiber NA of 0.22

	Divergence Angle (°)			
Core Diameter (μm)	.5	1	2	5
100	150	39	10.5	2.0
200	300	78	20.9	4.0
400	600	156	41.8	8.0
600	901	234	62.7	12.0

The basic surface contour used in non-imaging optics is that of a parabola[1]. However, in cases where narrow divergence angles indicate the need for very long light transformers, a combination of a lens and a modified (hyperbolic/parabolic) surface contour can be used to reduce the length of the LT. For certain geometries, a simple conical surface can be substituted for the hyperbola/parabola contour with minimal loss in collection efficiency.

For a hollow LT, the basic surface contour is that of a compound parabolic concentrator. Referring to FIG. 5, a surface contour of a compound parabolic concentrator (CPC) light transformer (LT) is depicted. Optical fiber 120

is connected to conical optical element 145. Conical optical element 145 composes part of nonimaging optic 140.In two dimensions, a CPC is made up of a parabolic section and a straight section rotated around the axis of symmetry of the optical element to form a paraboloid coupled to a straight-sided cone. The parabola's axis is aligned not with the axis of symmetry, but along the design's maximum acceptance angle q_1.

For a fiber having a numerical aperture of 0.22, light striking the fiber surface at an angle of more than 13° will not be coupled into the guiding modes of the fiber. For this reason, a conical optical element is introduced at the fiber end of the LT. The conical optical element can be an integral part of the NIO. In a one-dimensional cross section, this cone performs as a plane mirror that turns incident light at the maximum acceptance angle so that it is incident on the fiber face at 13°. For a 1° LT input acceptance angle, the cone half angle is 6°. The length of the straight-sided section can be determined directly from the reflection geometry.

Referring to FIG. 6, a reflection geometry of a CPC conical optical element section is depicted. The length of the straight section, ℓ, is given by:

$$\ell = d/(\tan(13°) - \tan(ø)), \qquad (4)$$

where d is the fiber diameter and ø the half angle of the cone formed by the straight section. For a 1° acceptance angle and a 400 μm diameter core fiber with a numerical aperture of 0.22, ø is 6°, ℓ is 3.18 mm, and the LT diameter at this point is 1.06 mm.

The determination of the parabolic contour requires a straightforward rotation and translation of the basic parabolic equation. The transformation is simplified if the polar coordinates defined in FIG. 7 are used.

Referring to FIG. 7, a polar coordinate system used to calculate the CPC parabolic curve is depicted. With this coordinate system:

$$r = 2f \sin(ø - \theta_{max})/(1 - \cos ø) - a; \qquad (5)$$

$$z = 2f \cos(ø - \theta_{max})/(1 - \cos ø), \qquad (6)$$

where f, the focal length of the parabola, is given by:

$$f = a(1 + \sin \theta_{max}). \qquad (7)$$

Eq. (7) is derived from the basic geometrical definition of the parabola: a collection of points equidistant from a fixed point and a line. Referring to FIG. 8, the geometric construction used to derive Eq. (7) is depicted.

Eqs. (5) and (6) follow directly from the geometries and coordinates defined in FIGS. 7 and 8. However, these equations assume a numerical aperture of unity for the parabolic LT. In the case of the reduced fiber optic numerical aperture (e.g., 0.22), the results need to be scaled down by a factor proportional to the numerical aperture. This scale factor can be achieved by redefining Eq. (7) as:

$$f = a\,(1 + \sin\theta_{max})\,(NA). \qquad (8)$$

Using Eqs. (4), (5) and (8), the contour of the parabolic section can be calculated.

c. LT-Lens Combinations for Reduced Length at Narrow Fields-of-View

As discussed above, designing a simple compound parabolic concentrator for a large core fiber and a narrow field-of-view results in an LT that is rather long for practical use. For a 400 μm core fiber and a 1° (half angle) field-of-view, the required length is approximately 6 in. An alternative approach is to use a hybrid LT-lens combination, which considerably reduces the length requirement. The more sophisticated design shown in FIG. 9 includes a convex plane lens integrated with the light transformer. For certain LT/lens combinations, the LT surface contour is very close to that of a simple cone. And such devices can be readily fabricated to produce a solid LT/lens combination fused directly to the end of the fiber.

The general surface contour for an LT/lens combination is a combination of a hyperbola, a parabola, and a spherical lens. Referring to FIG. 9, a general surface contour for an NIO/lens combination is depicted. Optical fiber 220 is connected to nonimaging optics 240. Refractive optics 250 are connected to nonimaging optics 240. Together with a non-Lambertian holographic surface diffuser (not shown) nonimaging optics 240 and refractive optics 250 compose a solid integrated beamformer. At the maximum design divergence angle, the focal points of the lens, the parabola, and the first focus of the hyperbola are coincident. Light striking the hyperbolic section of the LT is brought to a focus at the second focal point of the

hyperbola. Algorithms can be developed without undue experimentation utilizing a typical MATHCAD software package to optimize the combined LT/lens design.

d. Holographic Diffusers

In a preferred embodiment, the present invention uses a holographic surface diffuser. This method of light-beam shaping utilizes a holographically recorded diffuser with a random nonperiodic surface microstructure. This recording and processing technology allows a wide range of holographic non-Lambertian diffusers to be produced. These diffusers shape the beam by precisely controlling the light intensity spatial distribution. Various light patterns -- circular, elliptical, linear, even square and rectangular with light distribution from 100° to 1° or less along the horizontal and vertical axes -- can be formed.

Referring to FIGS. 10(a) and 10(b), elliptical non-Lambertian holographic diffuser performance is depicted. FIG. 10(a) is a computer-generated output profile; and FIG. 10(b) is a pattern photo.

Depending on the recording geometry, material parameters, exposure, processing conditions and time, the surface relief microstructure can be formed holographically on photopolymer. The resulting holographic photopolymer has various shapes, deepness and size.

Referring to FIGS. 11(a) and 11(b), microphotographs of holographic surface relief of two diffusers according to the present invention are depicted. FIG. 11(a) depicts the surface relief of a circular holographic diffuser. FIG. 11(b) depicts the surface relief of an elliptical holographic diffuser.

e. Theoretical Modeling of Non-Lambertian Holographic Diffusers

A discussion of the theoretical modeling of non-Lambertian diffusers follows. One of skill in the art can numerically compute the intensity of the angular spectrum of optical beams scattered by the non-Lambertian diffuser produced by coherent (laser) beam recording. The radiant intensity of the angular spectrum of the scattered beam, $J(\bar{s})$, is obtained as a function of the observation unit vector, $\bar{s}$, with respect to (S_x, S_y)-coordinates. The angular spectral distribution is computed as a function of recording geometry and incident beam.

For the rectangular aperture of the original diffuser the recording aperture has the form:

$$P(u,v)=rect(\frac{u}{L})rect(\frac{v}{W}) \tag{9}$$

where the rectangle rectus function is

$$rect(x)=1,\ for|x|\le\frac{1}{2};\ 0,\ for|x|>\frac{1}{2}. \tag{10}$$

f. Recording Geometry

The recording geometry illustrated in FIG. 12 has coordinates (u,v). The recording monochromatic plane wave 300 has a wavelength of λ_R. The rectangular recording aperture 310 of the primary non-Lambertian diffuser 320 was applied at a physical distance, h, from the non-Lambertian diffuser recording plate 330 (x,y). The size of the aperture is represented by (L,W).

Monochromatic Plane Wave Response

For the monochromatic normally incident plane wave, with a recording wavelength of λ, the monochromatic plane wave response is

$$J(s_x,s_y)=D\cos\theta\Lambda(\frac{s_x}{s'_{xo}})\Lambda(\frac{s_y}{s'_{yo}}) \tag{11}$$

where θ is the angle between the $\bar{s}$-unit vector and the z-axis (see FIG. 13), D is a proportionality constant, and $\Lambda(\ldots)$ is the triangular function defined by the coordinate $(-s'_{xo}, 0)$, $(+s'_{xo}, 0)$, and (0,1). Referring to FIG. 13, incident radiating beam 400 interacts with non-Lambertian diffuser 410. The cutoff-values of the directional cosines are

$$s'_{xo}=\sin\theta'_{xo}=\frac{L}{h}\frac{\lambda}{\lambda_R}=\frac{\lambda}{\lambda_R}s_{xo}=\frac{L}{h'};\ h'=h\frac{\lambda_R}{\lambda} \tag{12a}$$

$$s'_{yo}=\sin\theta'_{yo}=\frac{W}{h}\frac{\lambda}{\lambda_R}=\frac{\lambda}{\lambda_R}s_{yo}=\frac{W}{h'};\ h'=h\frac{\lambda_R}{\lambda} \tag{12b}$$

General System Response

Using linear system theory, we can formulate the general system response in the form of the system impulse response:

$$J(\bar{s}) = \int\int\int h(\bar{s} - \bar{s}_o,\lambda)\, I_o(\bar{s}_o,\lambda) d^2\bar{s}_o\, d\lambda \tag{13}$$

where I_o is the 3-D angular/spectral distribution of the incident beam intensity in the form:

$$I_o(\bar{s}_o, \lambda) = I_o(S_{ox}, S_{oy};\lambda) \tag{14}$$

This distribution is assumed to be Gaussian, for simplicity. Here, $d^2\bar{s}_o = ds_{ox}ds_{oy}$, and the system impulse response, h, is

$$h(\bar{s},\lambda)=A\cos\theta\int\int P(u,v)P[u-\frac{\lambda_R}{\lambda}hs_x,\ v-\frac{\lambda_R}{\lambda}hs_y]dudv \tag{15}$$

where the recording aperture function P(u,v) is typically assumed to be rectangular, as in Eq.(9), or Gaussian. It is seen then that, in general, the integration is in the following 5-D space is

$$(u,v;\ S_{ox},\ S_{oy};\ \lambda) \tag{16}$$

f. Surface Relief Replication

There are at least three major methods for forming a surface diffuser according to the present invention: casting, embossing, and injection molding. All methods use a "sub-master" -- a nickel electroform or hard epoxy replica from a holographically recorded surface relief on photopolymer. One technique for plane surface diffuser replication is illustrated in FIGS. 14(a)-14(g).

Referring to FIGS. 14(a)-(g), a nickel electroforming technique for submicron surface relief replication is well suited to low cost replication. FIG. 14a illustrates a holographic master recording step where a master hologram includes a photopolymer layer 500 adjacent a substrate layer 510. In FIG. 14b a silver coating 530 has been applied to photopolymer 500. In FIG. 14c, a nickle "silver master"

forming step is shown where the silver coated master holograpm has undergone electrolytic deposition of nickel silver master 540. In FIG. 14d, a nickel "silver master" separation step is shown where nickel silver master 540 is shown just after having been separated from the silver coated master holograpm. In FIG. 14e, a sub-master fabrication step of forming and separating is shown where a nickel submaster 550 is formed adjacent nickel silver master 540. In FIG. 14f, a shim (insert) fabrication step is shown where nickel submaster 550 has been separated and now provides the basis for replication of nickel shim 560. In FIG. 14g, the step of replication is shown where nickel shim 560 provides the basis for replication of plastic layer 570.

While the replication steps shown in FIGS. 14(a)-14(g) are directed to the fabrication of planar replication tools, spherical and aspherical tools can be similarly developed. Assuming a typical surface feature pitch of 0.3 microns, typical height aspect ratio would yield an average surface feature height of approximately 4 microns. Further, as long as the ratio of radius of curvature to pitch exceeds approximately 1000, planar embossing tools can be gently bent to form curved surfaces, thereby replicating curved shapes from initially planar tools.

3. Methods of Manufacture

The fabrication of the proposed solid integrated beamformer demands that both the optical quality and the dimensions be carefully controlled. In production, there are three basic manufacturing techniques that can be used. These are thermoforming, casting, and injection molding.

In thermoforming, a rod of cast, optical grade plastic (acrylic) is forced into a heated mold using a heated tool contoured to form a lens with the diffuser pattern. To form a spherical lens, a concave mold that includes a submaster of a surface diffuser relief pattern can be used. In casting, a mold is used that includes a concave lens tool surface and an NIO tool surface. The mold is filled with optical grade plastic monomer and the monomer is polymerized to form the NIO portion simultaneously with the lens portion, the later of which includes the diffuser relief pattern. The polymerized work piece is then removed from the mold. Initiators are usually added to speed up this process and the mold is typically heated. In injection molding, molten plastic is forced into a mold that includes a lens tool surface and an

NIO tool surface. Again, the lens tool surface includes the diffuser relief pattern. After the molten plastic cools, finished work piece is removed from the mold. In all cases, considerable care is required in controlling the temperature and the heating and cooling rates of the molds and the plastic. To maintain dimensional tolerances, the thermal expansion rates of the plastic and the mold must be considered.

Thermoforming, or high pressure cold forming, can be used with a single mold to produce limited production quantities of the hybrid optical elements. A typical thermoforming method would include: providing an optical blank with said distal refractive end; providing a surface diffuser master; contacting said distal refractive end with said diffuser master; and then removing said diffuser master from said distal refractive end.

Casting is the normal technique for producing simple shapes, particularly rods and tubes in optical grade acrylic. However, the dimensional changes during the polymerization process must be carefully considered. A typical casting process would include: providing a mold i) defining a void and ii) including a surface diffuser master; filling said mold with a molding material so as to fill said void and contact said surface diffuser master with said molding material; polymerizing said molding material; and removing said solid integrated beamformer from said mold. The use of acrylic, or other plastic monomers, requires the use of careful handling techniques to contain the vapor and avoid human exposure, possible fire risks, and environmental release.

Injection molding equipment and tooling are expensive and the production volume and allowable payback time must be high to justify the investment. A typical injection molding process would include: providing a mold i) defining a void and ii) including a surface diffuser master; injecting a molding material into said mold so as to fill said void and contact said surface diffuser master with said molding material; allowing said molding material to cool and removing said solid integrated beamformer from said mold.

Higher production rates can be achieved using injection molding techniques. Although the diffuser is more tolerant of optical inhomogeneities than conventional optical elements, careful process control is required to maintain optical quality.

Another method of manufacturing the solid integrated beamformer is laminating a surface diffuser to the distal refractive end. A typical laminating procedure would include: providing an optical blank with said distal refractive end; providing a surface diffuser layer; and attaching said surface diffuser layer to said distal refractive end.

However, the particular manufacturing process is not essential to the present invention as long as it provides the described transformation. Normally the manufacturers of this product will select the manufacturing process as a matter of design choice based upon tooling and energy requirements, in view of the expected application requirements of the final product and the demands of the overall manufacturing process.

The particular material used for the beam transformer should be suitable for the manufacturing process and the expected end-use conditions. Conveniently, the beamformer of the present invention can be made of any transparent thermoplastic material. It is preferred that the material be transparent in the visible spectrum. For the manufacturing operation, it is moreover an advantage to employ an acrylic or polycarbonate material.

However, the particular material selected is not essential to the present invention, so long as it provides the described function. Normally, the manufacturers of this product will select the best commercially available material as a matter of design choice based upon the economics of cost and availability, in view of the expected application requirements of the final product and the demands of the overall manufacturing process.

While not being limited to any particular evaluation technique, preferred embodiments of the present invention can be identified one at a time by testing for the presence of high definition. The test for the presence of high definition can be carried out without undue experimentation by the use of a simple and conventional light scattering assay experiment. Such scattering measurements can be performed using the automated scattering apparatus illustrated in FIG. 15. Referring to FIG. 15, a surface diffuser 600 (with, or without, a fiber-NIO/RO combination) is mounted on a stand 610 and illuminated with a collimated beam 620 from HeNe laser 630. The distribution of the light scattered in the forward direction is measured using a silicon

photodiode 640 mounted on a rotation arm 650. The entire system is fully automated and the light scattering data is automatically acquired, normalized, and plotted. Data obtained by swinging rotation arm 650 through arc 660 is acquired and analyzed by a data control and data acquisition system 670. The experiment can then be repeated using a fiber/NIO combination with white light illumination and the two scattering plots are compared.

EXAMPLE

A specific embodiment of the present invention will now be further described by the following, nonlimiting example which will serve to illustrate various features of significance. The example is intended merely to facilitate an understanding of ways in which the present invention may be practiced and to further enable those of skill in the art to practice the present invention. Accordingly, the example should not be construed as limiting the scope of the present invention.

Using Eqs. (4), (5) and (8), the contour of the parabolic section can be calculated. For the case of a 1° divergence angle and a 400μm core fiber, the contour is given in Table 2.

Table 2
Nonimaging optics contour calculated from Eqs. (4), (5), and (8); optical fiber diameter is 0.4 mm, NA is 0.22, NIO divergence angle is 1°

ϕ	r	z
14	0.48	2.94
13	0.53	3.42
12	0.58	4.02
11	0.65	4.80
10	0.72	5.82
9	0.81	7.20
8	0.92	9.13
7	1.06	11.95
6	1.22	16.28
5	1.44	23.47
4	1.72	36.71
3	2.08	65.29
2	2.37	146.96

The benefits of remote source lighting include high efficiency, reduced power consumption, reduced life-cycle costs, increased ease of use and reduced maintenance and repair, much higher reliability and, optionally, redundancy. The benefits of remote source lighting are clearly of interest to those who light airports, ammunition storage areas, toxic sites, inaccessible areas, signal and warning lights. These advantages include permanent and water tight installation.

Applications where safety or convenience of maintenance are of particular importance are especially good candidates for the use of remote lighting. With the availability of low cost, mass-producible solid integrated beamformers, remote source lighting products will be more affordable and thus able to reach an even wider market.

Practical applications of the present invention which have value within the technological arts are airport lighting, obstruction lighting, task lighting, and marine lighting. Further, all the disclosed embodiments of the present invention are useful

in conjunction with specialty light applications such as ship, aircraft, and boat-mast lighting, or for the purpose of environmental control light applications such as cold light in medical operating rooms, high bay lighting, mine area lighting, refinery distillation area lighting, and underwater lighting, or the like. Similarly, safety-related lighting applications are candidates for the use of remote lighting.

As a specific practical application, the Defense Explosive Safety Board currently requires the use of vapor-tight explosion-proof light fixtures in all explosive environments. Whenever a bulb requires replacement, all flammable materials (stored or work-in-process) must be removed from the room and the fixture cleaned with steam to remove explosive particles before bulb replacement. The use of remote source lighting, with the illumination source outside the room, would cut the capital cost of such fixtures. Further, maintenance costs and down time for illumination source replacement would also be reduced.

The same rationale applies to paint booths, which have safety imposed restrictions requiring vapor-tight light fixtures. Again, placing the illumination source outside the booth would eliminate the need to use the expensive fixtures.

In traffic and road signage, replacing bulbs is a major expense because the lighting is usually high overhead and in remote locations, driving maintenance labor costs very high. With remote lighting, the illumination source can be conveniently placed at ground level, eliminating the need for cherry-pickers and other expensive support equipment.

The applications described above have a high probability for adopting remote lighting because of facility safety considerations. For example, the high costs of currently used explosion proof and hazardous area fixtures make remote lighting very attractive for these applications. There are virtually innumerable uses for the present invention described herein, all of which need not be detailed here.

The present invention described herein provides substantially improved results that are unexpected. The present invention described herein can be practiced without undue experimentation. The entirety of everything cited above or below is hereby expressly incorporated by reference.

Although the best mode contemplated by the inventors of carrying out the present invention is disclosed above, practice of the present invention is not limited

thereto. It will be manifest that various additions, modifications and rearrangements of the features of the present invention may be made without deviating from the spirit and scope of the underlying inventive concept.

For example, performance could be enhanced by providing more complicated NIO shapes. Similarly, although acrylic or polycarbonate is preferred for the solid integrated beamformer, any suitable material could be used in its place. In addition, the individual components need not be fabricated from the disclosed materials, but could be fabricated from virtually any suitable materials.

Moreover, the individual components need not be formed in the disclosed shapes, or assembled in the disclosed configuration, but could be provided in virtually any shape, and assembled in virtually any configuration, which function so as to provide a distal end for RSL. Further, although the solid integrated beamformer described herein is a physically separate module, it will be manifest that the solid integrated beamformer may be integrated into the apparatus with which it is associated. Furthermore, all the disclosed features of each disclosed embodiment can be combined with, or substituted for, the disclosed features of every other disclosed embodiment except where such features are mutually exclusive.

It is intended that the appended claims cover all such additions, modifications and rearrangements. Expedient embodiments of the present invention are differentiated by the appended subclaims.

REFERENCES

1. W. Wheeler, U.S. Pat. No. 247,229, 1880.
2. W.T. Welford & R. Winston, "High Collection Nonimaging Optics", Academic Press, Inc., San Diego, CA, 1989.
3. H. Hittenberger, R. Winston, Proc. Int. Conf. Instrum. High Energy Phys., "Gas Cerenkov counter with optimized light collection efficiency."
4. H. Hittenberger, R. Winston, Rev. Sci. Instrum. 37 1094-1095 (1966), "Efficient light coupler for threshold Cerenkov counters."
5. D. Cooke, Applied Optics 31(6) 7541-7546 (1992), "Sun pumped lasers: revisiting an old problem with nonimaging optics."
6. N. Fraidenraich, Applied Optics 34(22) 4800-4811 (1995), "Analytic solutions for the optical and radiative properties of nonaccepted light radiation of V trough concentrators."
7. K-P Ho & J.M. Kahn, Optical Engineering 34(5) 1385-1395 (1995), "Compound parabolic concentrators for narrowband wireless IR receivers."
8. B. Moslehi, J. Ng, I. Kasimoff, & T. Jannson, Optics Letts. 14(23) 1327-1329 (1989), "Fiberoptic coupling based on nonimaging expanded beam optics."
9. S.A. Evanson & A.H. Rawicz, Applied Optics 34(31) 7302-7306 (1995), "Thin film luminescent concentrators for integrated devices: a cookbook."
10. D.J. Ferrell, J.M. Lerner, R.A. Lieberman, T. Quintana, E.M. Schmidlin, & S.J. Syracuse, Optical Engineering 32(3) 504-507 (1993), "Instrumentation systems for passive fiber optic chemical sensors."
11. A. Cutolo, L. Carlomusto, F. Reale, & I. Rendina, Applied Optics 29(9) 1353-1364 (1990), "Tapered and inhomogeneous dielectric light concentrators."
12. G.J. Pendock, H.S. MacKenzie, & F.P. Payne, Applied Optics 32(27) 5236-5242 (1993), "Dye lasers using tapered optical fibers."

13. B.D. Gupta & C.D. Singh, Applied Optics 33(13) 2737-2742 (1994), "Evanescent absorption coefficient for diffuse source illumination: uniform and tapered fiber sensors."

14. I. Agurok, L. Sadovnik, A. Rizkin. Light Transformer Design Optimization, OSA Conference, Portland, OR, 1995.

15. Van Nostrand's Scientific Encyclopedia, 8th ed., Van Nostrand Reinhold, (Douglas M. Considine et al. eds., 1995).

16. Handbook of Optics, 2nd ed., Vols. I-II, McGraw Hill, (Michael Bass et al. eds., 1995).

17. Bahaa E.A. Saleh & Malvin C. Teich, Fundamentals of Photonics, John Wiley & Sons, (1991).

CLAIMS

What is claimed is:

1. A solid integrated beamformer comprising:

a solid nonimaging optic having i) a proximal nonimaging end and ii) a distal nonimaging end;

a solid refractive optic integrally attached to said distal nonimaging end, said solid refractive optic including a distal refractive end; and

a non-Lambertian holographic surface diffuser integrally formed on said distal refractive end.

2. A method of making the solid integrated beamformer of claim 1, comprising providing a mold i) defining a void and ii) including a surface diffuser master;

filling said mold with a molding material so as to fill said void and contact said surface diffuser master with said molding material;

polymerizing said molding material; and

removing said solid integrated beamformer from said mold,

wherein the steps of filling and removing compose casting said non-Lambertian holographic surface diffuser.

3. A method of making the solid integrated beamformer of claim 1, comprising providing an optical blank with said distal refractive end;

providing a surface diffuser master;

contacting said distal refractive end with said diffuser master; and then

removing said diffuser master from said distal refractive end,

wherein the steps of contacting and removing compose replicating said non-Lambertian holographic surface diffuser.

4. A method of making the solid integrated beamformer of claim 1, comprising providing an optical blank with said distal refractive end;

providing a surface diffuser layer; and

attaching said surface diffuser layer to said distal refractive end,

wherein the steps of providing and attaching compose laminating said non-Lambertian holographic surface diffuser.

5. A system, comprising at least two of the solid integrated beamformer of claim 1.

6. A method, comprising utilizing the solid integrated beamformer of claim 1.

7. An apparatus, comprising: a solid integrated beamformer, said solid integrated beamformer including:

nonimaging optics;

refractive optics integrally attached to said nonimaging optics; and

a non-Lambertian holographic surface diffuser integrally attached to said refractive optics.

8. The apparatus of claim 7 wherein said nonimaging optics include a compound parabolic concentrator, said refractive optics include a distal refractive end and said non-Lambertian holographic surface diffuser is formed on said distal refractive end.

9. The apparatus of claim 8 wherein said nonimaging optics include a conical optical element.

10. The apparatus of claim 7 wherein said nonimaging optics include a conical optical element.

11. A method of making the apparatus of claim 7, comprising providing a mold i) defining a void and ii) including a surface diffuser master;

filling said mold with a molding material so as to fill said void and contact said surface diffuser master with said molding material; and

removing said solid integrated beamformer from said mold,

wherein the steps of filling and removing compose casting said non-Lambertian holographic surface diffuser.

12. A method of making the apparatus of claim 7, comprising providing an optical blank with said refractive optics;

providing a surface diffuser master;

contacting said refractive optics with said diffuser master; and then

removing said diffuser master from said refractive optics,

wherein the steps of contacting and removing compose replicating said non-Lambertian holographic surface diffuser.

13. A method of making the apparatus of claim 7, comprising providing an optical blank with said refractive optics;

providing a surface diffuser layer; and

attaching said diffuser to said refractive optics,

wherein the steps of providing and attaching compose laminating said non-Lambertian holographic surface diffuser.

14. A system, comprising at least two of the apparatus of claim 7.

15. A method, comprising utilizing the apparatus of claim 7.

16. A method, comprising:

providing a mold i) defining a void and ii) including a surface diffuser master;

filling said mold with a molding material so as to fill said void and contact said surface diffuser master with said molding material; and then

removing a solid integrated beamformer from said mold.

17. An apparatus for performing the method of claim 16.

18. A product made by the method of claim 16.

19. A method, comprising:

providing an optical blank with a nonimaging optic and a refractive optic, said refractive optic having a distal refractive end;

providing a surface diffuser master;

contacting said distal refractive end with said diffuser master; and then

removing said diffuser master from said distal refractive surface so as to replicate said surface diffuser master on said distal refractive end.

20. An apparatus for performing the method of claim 19.

21. A product made by the method of claim 19.

22. A method comprising:

providing an optical blank with a nonimaging optic and a refractive optic, said refractive optic including a distal refractive end;

providing a surface diffuser layer; and then

attaching said surface diffuser layer to said distal refractive end,

wherein the steps of providing and attaching compose laminating said surface diffuser layer to said distal refractive end.

23. An apparatus for performing the method of claim 22.

24. A product made by the method of claim 22.

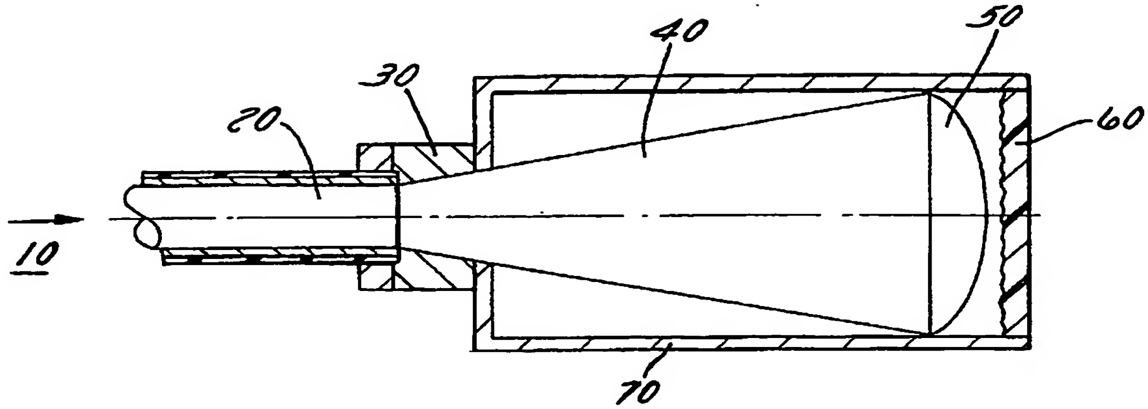

FIG. 1

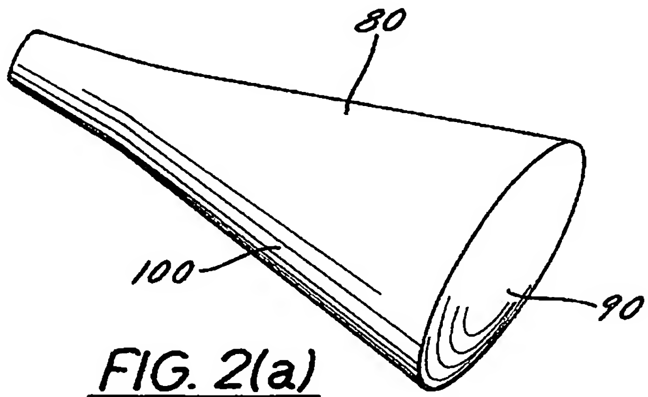

FIG. 2(a)

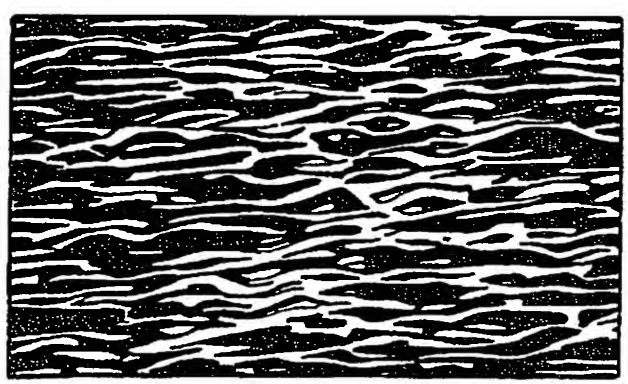

FIG. 2(b)

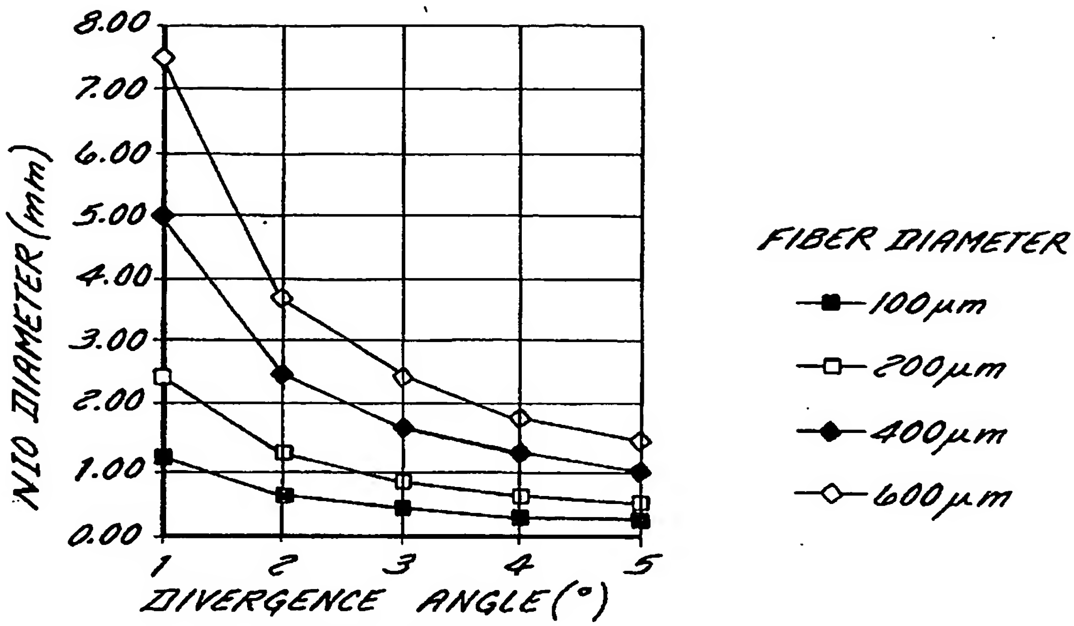
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
NIO DIAMETER (mm)
1
2
3
4
5
DIVERGENCE ANGLE (°)
FIBER DIAMETER
100μm
200μm
400μm
600μm

FIG. 3(a)

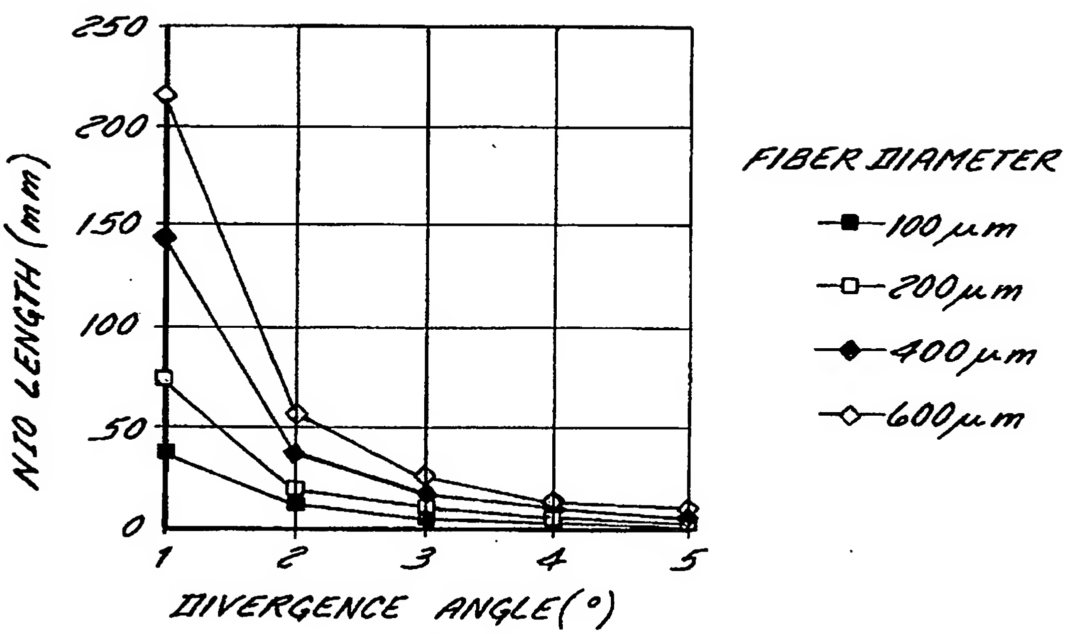
250
200
150
100
50
0
NIO LENGTH (mm)
1
2
3
4
5
DIVERGENCE ANGLE (°)
FIBER DIAMETER
100μm
200μm
400μm
600μm

FIG. 3(b)

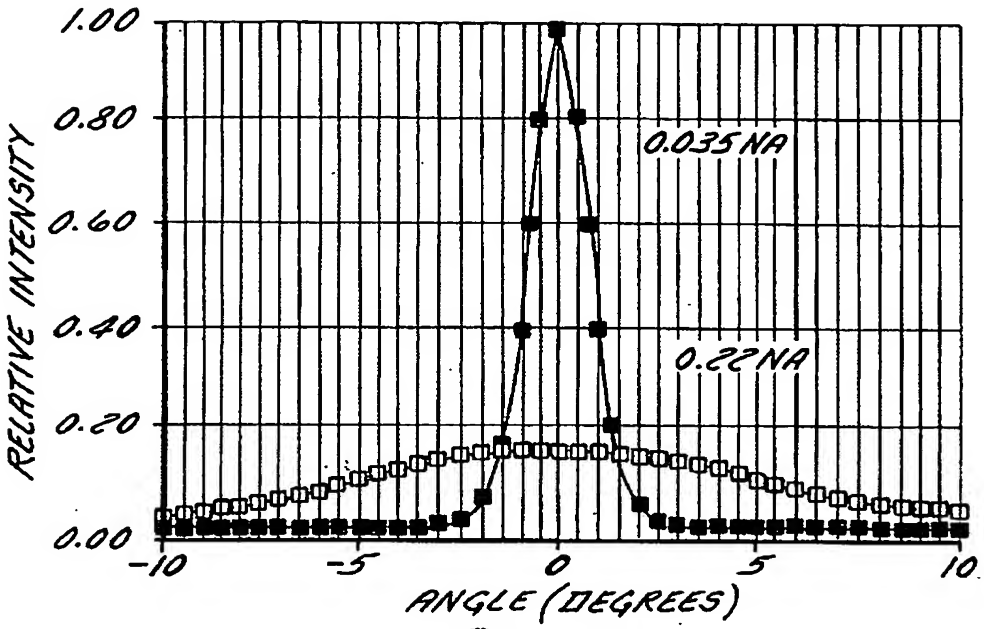
1.00
0.80
0.60
0.40
0.20
0.00
RELATIVE INTENSITY
0.035 NA
0.22 NA
-10
-5
0
5
10
ANGLE (DEGREES)

FIG. 4(a)

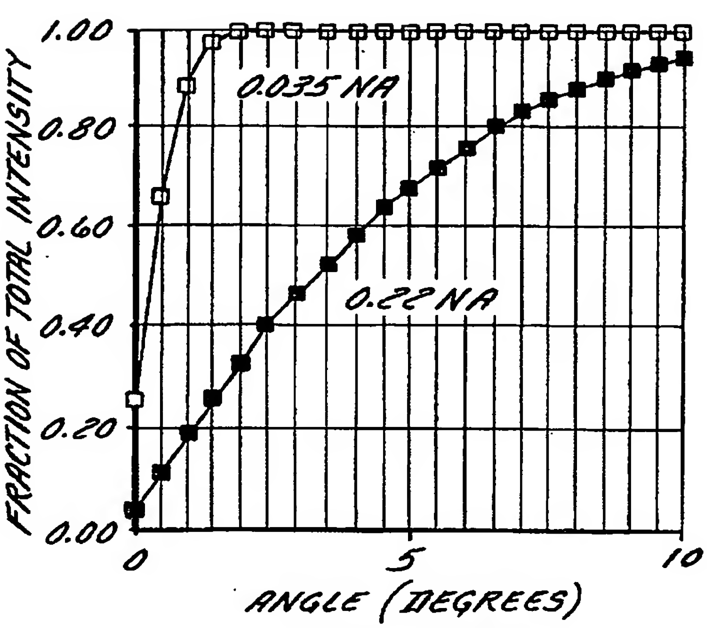
1.00
0.80
0.60
0.40
0.20
0.00
FRACTION OF TOTAL INTENSITY
0.035 NA
0.22 NA
0
5
10
ANGLE (DEGREES)

FIG. 4(b)

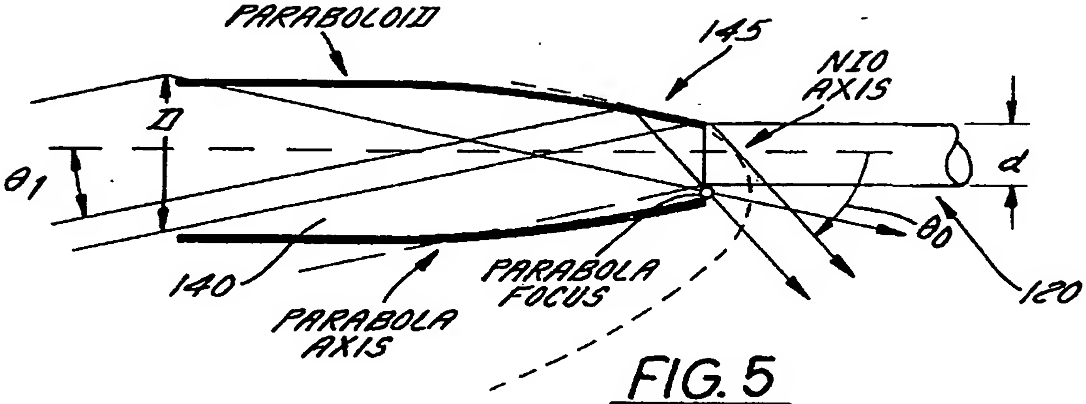

FIG. 5

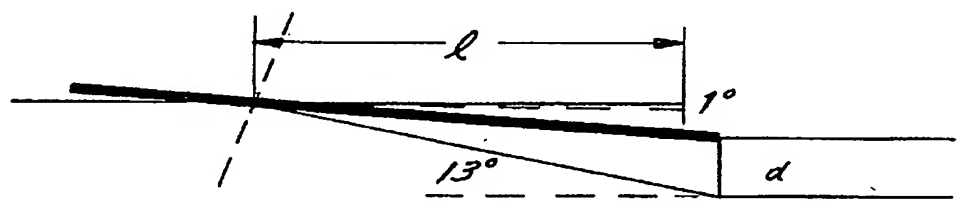

FIG. 6

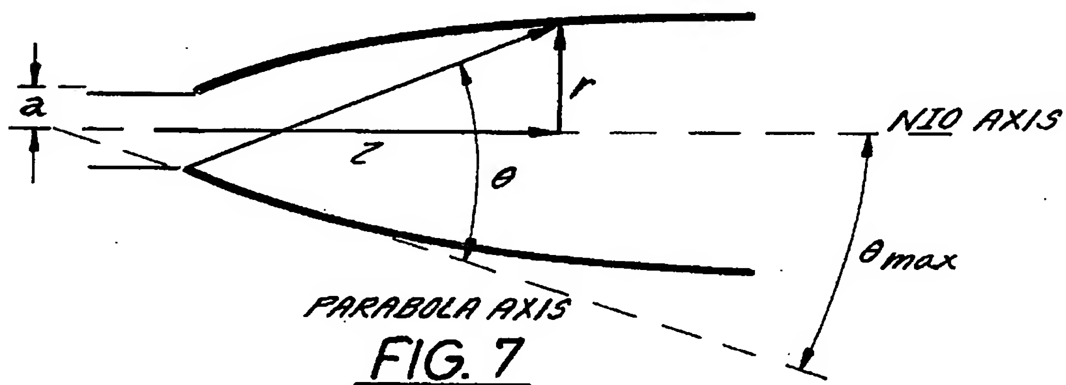

FIG. 7

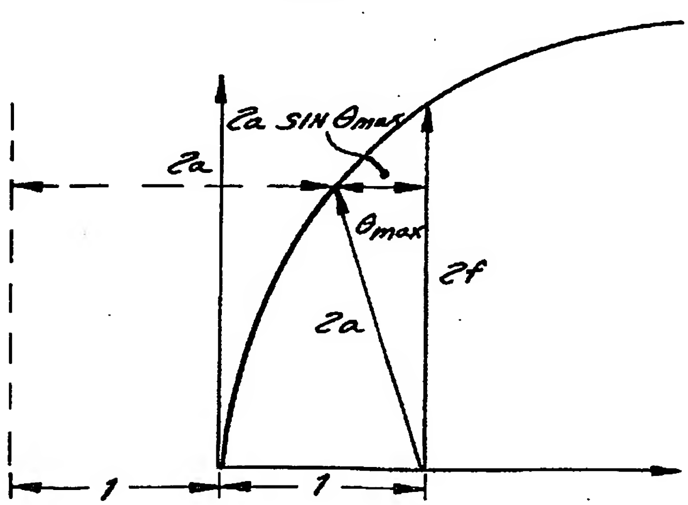

FIG. 8

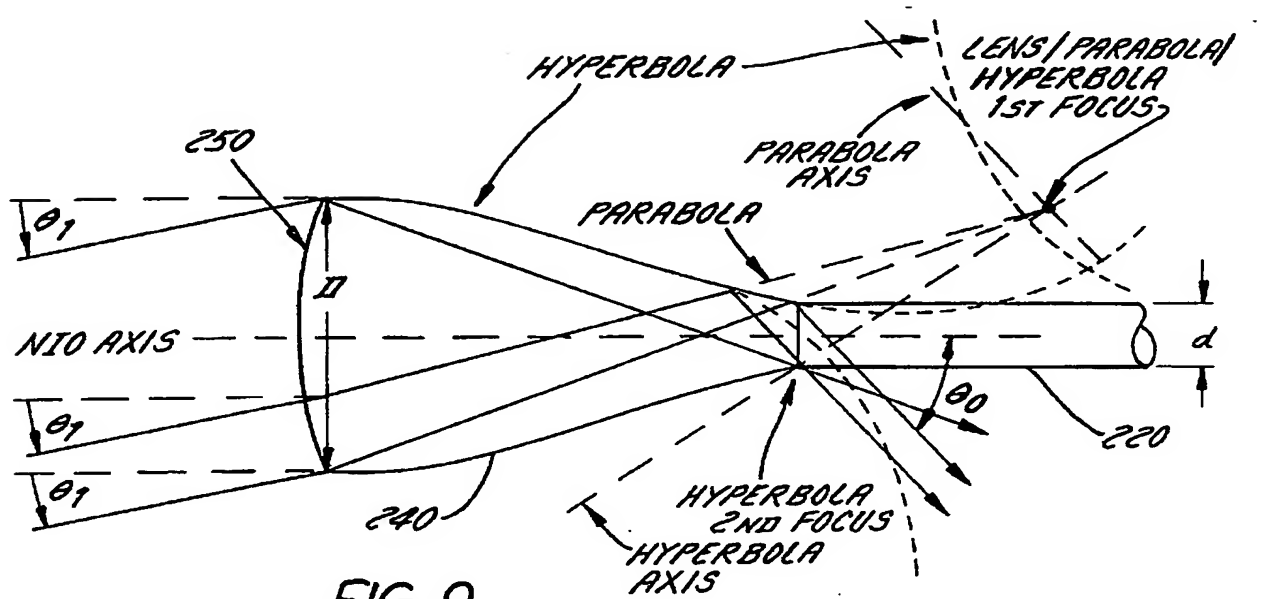

FIG. 9

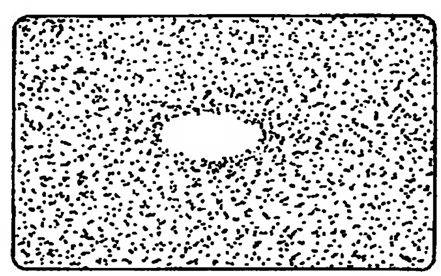

FIG. 10(b)

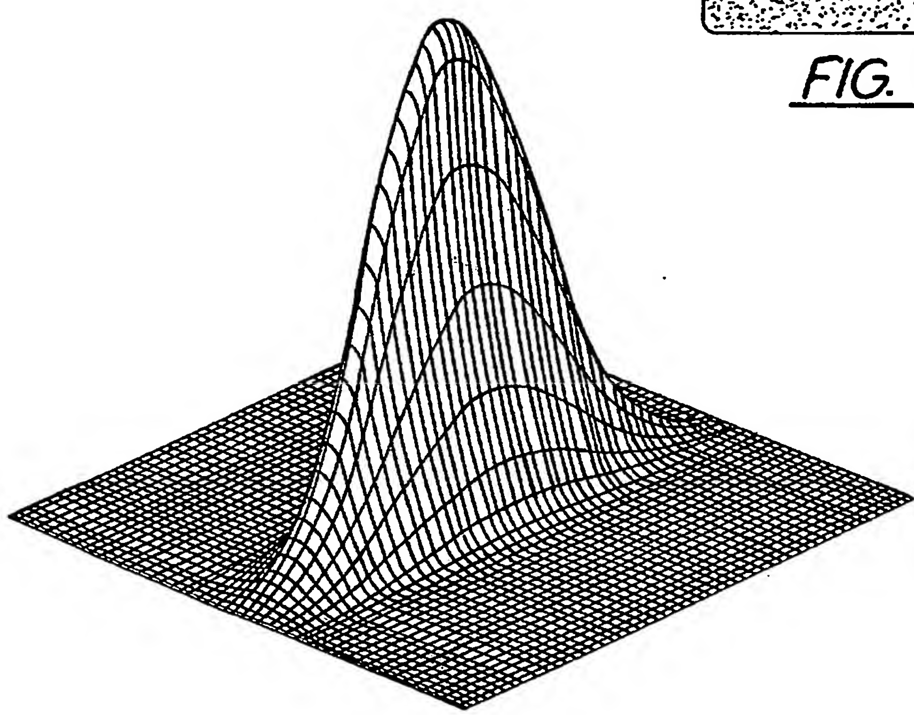

FIG. 10(a)

FIG. 11(a)

FIG. 11(b)

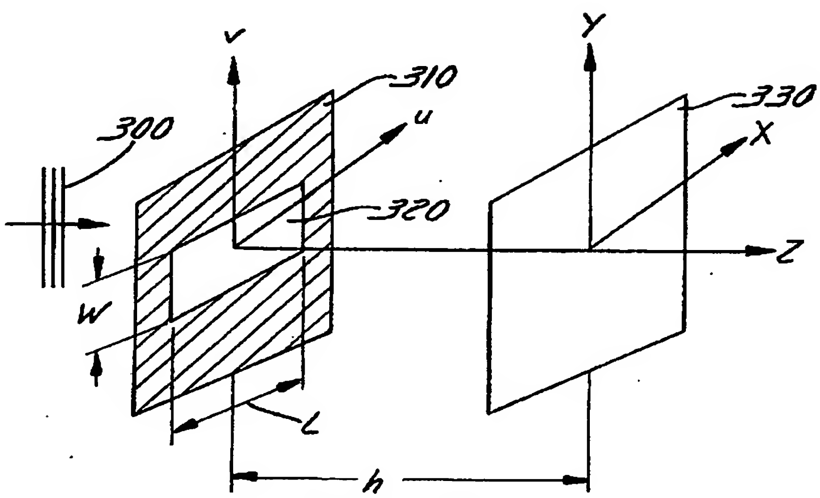

FIG. 12

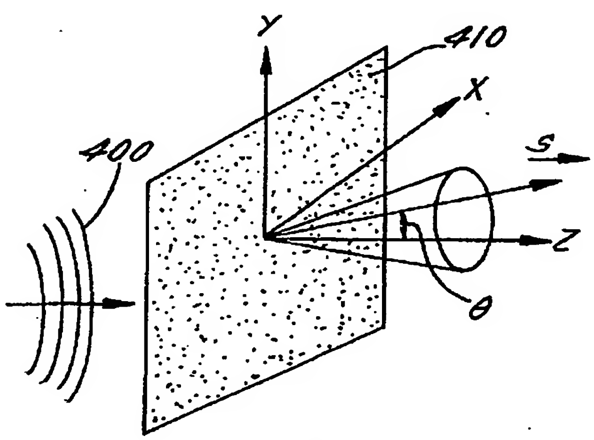

FIG. 13

FIG. 14(a)

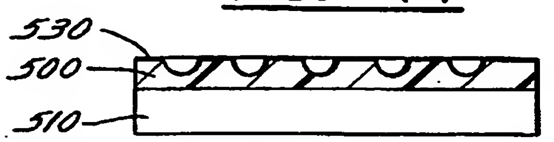

FIG. 14(b)

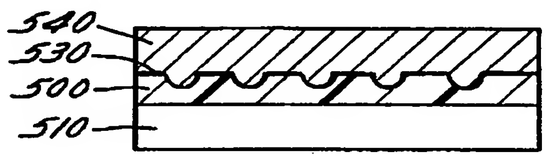

FIG. 14(c)

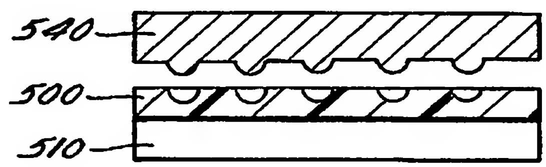

FIG. 14(d)

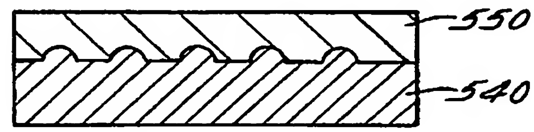

FIG. 14(e)

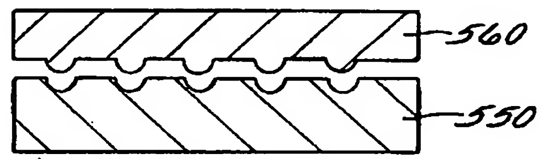

FIG. 14(f)

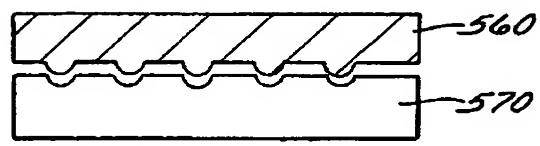

FIG. 14(g)

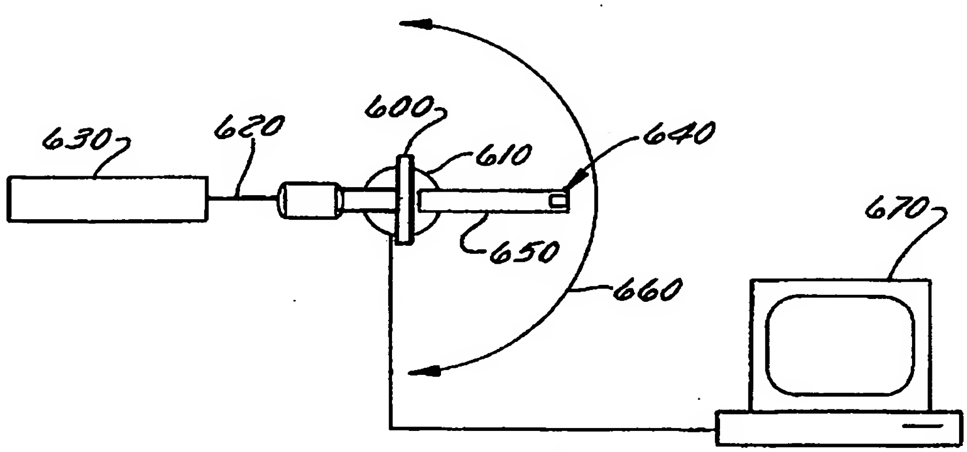

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/19500

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :F21V 7/04, 8/00; G02B 5/32; G03H 1/00,
US CL :359/15, 34; 385/31, 147; 262/32
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/15, 31, 34; 385/31, 123, 147; 362/32

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS
holographic diffuser, beamformer, concentrator, transformer,nonimaging optics.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US 5,629,996 A (RIZKIN et al) 13 May 1997 (13/05/97), see Figures 2, 4, 12a, 12b, 20, 26, columns 13-14 and 17.	1-24

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 30 JANUARY 1998	Date of mailing of the international search report 02 MAR 1998
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer For AUDREY CHANG Telephone No. (703) 305-6208

Form PCT/ISA/210 (second sheet)(July 1992)★